An inverse relationship between production and export efficiency in the Southern Ocean

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[1] In the past two decades, a number of studies have been carried out in the Southern Ocean to look at export production using drifting sediment traps and thorium-234 based measurements, which allows us to reexamine the validity of using the existing relationships between production, export efficiency, and temperature to derive satellite-based carbon export estimates in this region. Comparisons of in situ export rates with modeled rates indicate a two to fourfold overestimation of export production by existing models. Comprehensive analysis of in situ data indicates two major reasons for this difference: (i) in situ data indicate a trend of decreasing export efficiency with increasing production which is contrary to existing export models and (ii) the export efficiencies appear to be less sensitive to temperature in this region compared to the global estimates used in the existing models. The most important implication of these observations is that the simplest models of export, which predict increase in carbon flux with increasing surface productivity, may require additional parameters, different weighing of existing parameters, or separate algorithms for different oceanic regimes. **Citation:** Maiti K., M. A. Charette, K. O. Buesseler, and M. Kahru (2013), An inverse relationship between production and export efficiency in the Southern Ocean, *Geophys. Res. Lett.*, *40*, 1557–1561, doi:10.1002/grl.50219.

1. Introduction

[2] The Southern Ocean is a major conduit for gas exchange between the atmosphere and the ocean interior, accounting for almost 20% of the global ocean CO_2 uptake [*Takahashi et al.*, 2002], and thereby contributing to the regulation of both atmospheric CO_2 levels and deep ocean O_2 levels. Global models indicate that it acts as a net sink for atmospheric CO_2 mainly due to CO_2 fixation by phytoplankton and subsequent downward particle flux of biogenic carbon [*Keeling and Peng*, 1995; *Toggweiler et al.*, 2003]. Of the organic material generated by primary production in the surface ocean, most is recycled, with only about 15–25% exported below 100 m [*Henson et al.*, 2011]. However, the controls on export appear be temporally and regionally variable such that it is not always directly proportional to the local primary production levels [e.g., *Buesseler et al.*, 1998]. At present, the processes governing the rate and magnitude of the export of particulate C and other nutrients from the upper ocean are key uncertainties in studies and models that highlight the Southern Ocean's role in regulating the global carbon cycle both at present and under changing climate.

[3] In the Southern Ocean very little in situ data are available to estimate export efficiencies, hence modeling approaches are often used to predict export. One of the most commonly applied modeling approaches involves a steady state food web model that uses surface temperature and satellite-derived primary production (net primary production, NPP) to derive export efficiency [*Laws et al.*, 2000; *Laws* 2004] (henceforth referred to as Laws-00). This widely used empirical relationship is calibrated against data from 11 sites worldwide out of which only one study site falls in the domain of Southern Ocean (Ross Sea). Recently *Laws et al.* [2011] (henceforth referred to as Laws-11) published a simplified model that assumes a negative linear correlation with temperature and positive curvilinear correlation with primary production using a more comprehensive dataset [*Dunne et al.*, 2005]. *Schlitzer* [2002] applied an inverse approach with a coupled global ocean circulation-biogeochemical model to determine rates of export production and vertical carbon fluxes in the Southern Ocean. This model was fitted to the existing hydrological data by systematically varying circulation, air-sea fluxes, production, and remineralization rates simultaneously.

[4] Since the seminal paper by *Laws et al.* [2000] and the inverse model proposed by *Schlitzer* [2002], a number of studies were carried out in the Southern Ocean to look at export production using shallow sediment traps and ^{234}Th-based measurements. This paper looks at existing in situ export data for the Southern Ocean and reexamines the validity of using the existing relationships between production, export efficiency, and temperature to derive carbon export in this region.

2. Methods

[5] For the present study we compiled the published POC flux data for the Southern Ocean, collected using two different techniques: surface tethered cylindrical sediment traps and ^{234}Th-based measurements. In the present work Southern Ocean is defined as the region beyond 40°S following the Rutgers masks for different ocean basins (Rutgers University data available at http://marine.rutgers.edu/opp/Mask/Mask1.html).

All supporting information may be found in the online version of this article.

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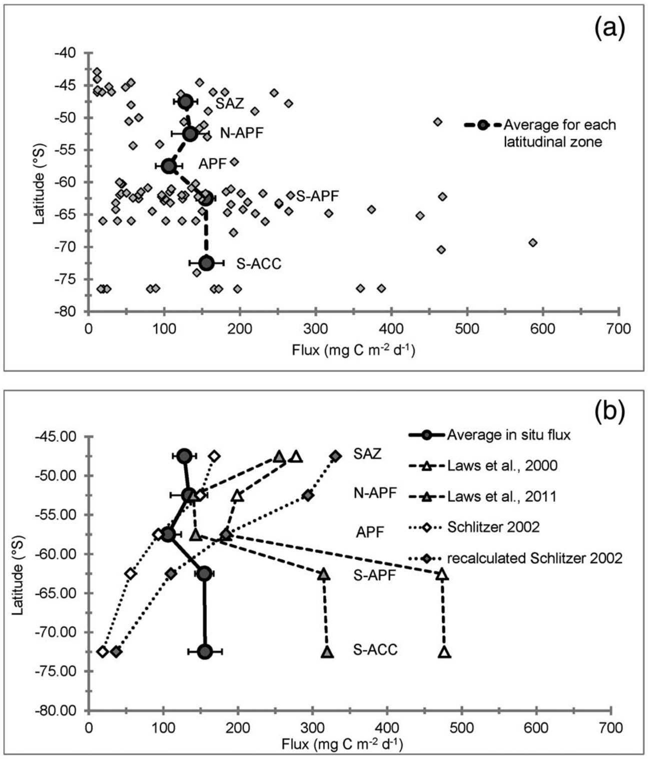

Figure 1. (a) The latitudinal trend in fluxes overlaid on the available data points. (b) Comparison of the observed data with estimates from *Schlitzer* [2002] inverse model, *Laws et al*. [2000] food web model, and *Laws et al*. [2011] best-fit equation. Error bar shows standard error of the mean.

Two criteria were established during the compilation of this dataset: (i) Only flux data from 100 ± 10m are included, and (ii) no data published before 1987 are included due to uncertainties with trap configurations. The trap-based flux data reported in this dataset are all collected using surface-tethered particle interceptor trap, fitted with multiple cylindrical tubes and deployed for 2–4 days [*Knauer et al*., 1979]. Three data points which have export efficiencies >1 are not considered in this study. Most of the flux data reported in the literature were from the months of October to April, with little to no data available for the months of May to September (Figure 1a). Out of the 140 stations, 136 reported export fluxes at exactly 100 m. For the other stations, no corrections were made for flux attenuation with depth and the changes are assumed to be negligible for 10 m or less. The compiled dataset also includes the directly measured primary production rates for each of these stations, as reported in literature. Satellite-derived sea surface temperature (SST) for corresponding stations were derived from AVHRR Pathfinder Version 5.0 8 day 4 km datasets (auxiliary material at http://www.nodc.noaa.gov/SatelliteData/pathfinder4km/) described by *Casey et al*. [2010].

[6] Modeled flux estimates (open and solid triangle in Figure 1b) derived from the relationship between temperature and export efficiency [*Laws et al*., 2000; *Laws et al*., 2011] are calculated by utilizing the directly measured primary production rates reported in literature and the satellite-derived SST for each station.

[7] The annual estimate of POC export from the inverse model of *Schlitzer* [2002] is recalculated to average daily export rates using 180 days (solid diamond in Figure 1b) instead of 365 days (open diamond in Figure 1b). Given that more than 90% of the export production in this region takes place between October and March, this scaling is more appropriate for comparison purposes. It must be also noted that all export values for this model were reported at 133 m with an estimated vertical attenuation of b = 1.04 for POC fluxes in the Southern Ocean [*Schlitzer*, 2002]. Thus, appropriate correction has been made to the modeled data to represent flux at 100 m by using this above mentioned b value.

3. Results and Discussion

[8] In order to better understand the trends in export flux across the Antarctic basin, the data are binned into five latitudinal bands. The five zones defined are the following: sub-Antarctic zone (SAZ) <55°S (33 stations), north of the Antarctic Polar Front (N-APF) 55°S–60°S (16 stations), Antarctic Polar Front (APF) 55°S–60°S (13 stations), south of the Antarctic Polar Front (S-APF) 60°S–65°S (43 stations), south of the Antarctic Circumpolar Current (S-ACC) >65°S (35 stations). The wide spatial and seasonal variability in the location of APF and ACC across the basin [*Orsi et al*., 1995] makes it difficult to delineate frontal zones based upon fixed latitudinal bands across the entire basin. Therefore, this banding does not comprehensively encompass the fronts, and the patterns shown should be treated more as a longitudinal trend rather than a frontal trend.

[9] The analysis of carbon export flux data reported at 100 m shows large spatial and temporal variability from 10 to 600 mg C m^{-2} d^{-1} (Figure 1a). The highest average POC flux rates of (standard error) 150 ± 12 mg C m^{-2} d^{-1} are found south of the APF band which is similar to what most studies have observed in the past [*Buesseler et al*., 1998, 2001]. The rates of POC export on sinking particles are high here relative to the other regions due to the combination of high nutrients, low grazing pressure, and efficient transport of POC to the depth [*Salter et al*., 2007; *Coppola et al*., 2005; *Buesseler et al*., 2001]. Patchiness as well as large seasonal and temporal variability in export fluxes makes it difficult to generalize about the latitudinal trend in export fluxes in this region.

[10] The in situ export fluxes are also compared with the flux estimates derived from the relationship between temperature and export efficiency [*Laws et al*., 2000, 2011; *Laws* 2004]. In general, the estimates from Laws-00 model overestimate the in situ export flux by a factor of 4 south of the APF and by a factor of 2 north of the APF (open triangle in Figure 1b). The Laws-11 parametric equation results in similar longitudinal pattern as in Laws-00 but the flux rates are lower by a factor of 2. Hence, Laws-11 provides flux estimates which are greater by a factor of 2 south of APF and are similar to the in situ estimates north of APF, with the exception of SAZ, where it is greater by a factor of 1.5.

[11] Comparison of *Schlitzer* [2002] model data with in situ flux estimates (solid circle in Figure 1b) indicates overestimation by a factor of 2 or more north of APF and underestimation by factor of 2 or more south of it. The overestimation of export production by Schlitzer's model with respect to the in situ trend is not surprising. The model was previously found to have systematically higher values (by factors between 2 and 5) than the satellite-based values

south of 50°S even though there was relatively good agreement over the rest of the global ocean [*Schlitzer*, 2002]. This discrepancy was attributed to the inability of the satellite sensors to detect frequently occurring sub-surface chlorophyll patches and to a poor calibration of the conversion algorithms in the Southern Ocean because of the very limited amount of direct measurements [*Schlitzer*, 2002]. However, the lower than expected values, south of the APF, cannot be explained by such an argument.

[12] The deviation of Laws-00 model from in situ flux data has important ramifications, as it forms the basis for most of the commonly used models to convert satellite-derived primary production and SST to export production. In general, the Laws-00 model predicts that under steady state conditions and at a constant temperature, the export efficiency should increase exponentially with an increase in primary production. Any increase in temperature in the model is attributed to higher metabolic demand and should lead to a decrease in the export ratio. In Figure 2a the in situ export fluxes and the export fluxes derived from Laws model uses the same primary productivity data reported in the literature for these studies. Since most of the published data do not report in situ water temperature during the time of sampling, satellite-derived temperatures are used here which could lead to some uncertainty. However, as shown in Figure 2a (black lines), the export efficiency and hence export flux for a given primary production can vary by a factor of 2 only if the temperatures are inaccurate by 12°C. This is highly unlikely and cannot explain the fourfold differences in the export fluxes observed between the in situ and Laws-00 model.

[13] The estimates using the simple best fit Laws-11 equation show a factor of 2 lower export production compared to the original Laws-00 model and probably reflects the fact that the former is derived from multiple export/new production measurement techniques (^{234}Th-based, sediment-trap based, and nitrate based) while the latter is derived entirely from only a limited number of estimates of new production based on nitrate uptake. This is probably an upper limit for new production given the amount of nitrification taking place in the euphotic zone [*Yool et al.*, 2007] and will result in higher export efficiency for Laws-00 model (Figure 2a, black lines) compared to the Laws-11 equation (Figure 2a, gray lines). The other important difference between the two approaches is the export efficiency derived from Laws-11 is much less sensitive to temperature than the Laws-00 model, with the most temperature sensitive regime shifted towards the higher end of primary production ($>2500\,\mathrm{mg\,C\,m^{-2}\,d^{-1}}$) compared to the Laws-00 model where the export efficiency is most sensitive for lower rates of primary production ($<1000\,\mathrm{mg\,C\,m^{-2}\,d^{-1}}$). Since most of the satellite-based estimates are based on the original Laws-00 model, we limit our discussion to that model for rest of the manuscript.

[14] It is clear from Figure 2a, that the Laws-00 model predicts the export efficiency to increase exponentially with increase in primary production. However, the in situ flux data is suggestive of a more complex relationship between export and production that appears to be inverse i.e., export efficiency increases with a decrease in primary production. A number of previous studies have noted high POC export relative to the primary production [*Rutgers van der Loeff et al.*, 2002; *Buesseler et al.*, 2001] indicating a high efficiency for particle export that is decoupled from changes in surface chlorophyll or primary production maxima earlier in the season. Although not well understood this could be partially attributed to low grazing rates in the region and sinking of intact diatoms in response to nutrient limitation or mixing (*Buesseler et al.*, 2001; *Coppola et al.*, 2005].

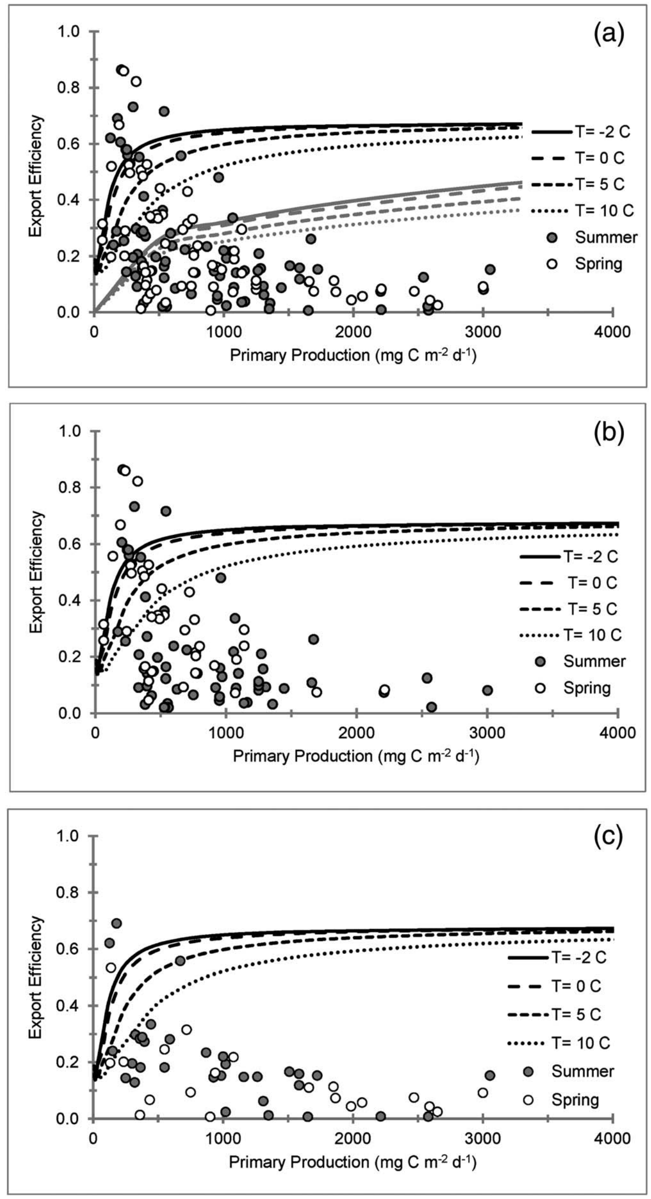

Figure 2. Relationship between export efficiency and primary production based on modeled and observed data. The black lines are based on *Laws et al.* [2000] model and the grey lines are based on *Laws et al.* [2011] equation. The complete flux dataset shown in Figure 2a is further subdivided into ^{234}Th-based measurements which are shown in Figure 2b and sediment trap-based measurements which are shown in Figure 2c.

[15] This apparent discrepancy between in situ and modeled fluxes holds whether using ^{234}Th-based fluxes (Figure 2b) or sediment trap fluxes (Figure 2c), with open circles representing spring (October–December) and filled circles representing summer (January–March). In both instances, there is a systematic deviation from the trend predicted by Laws-00 model, which rules out differences

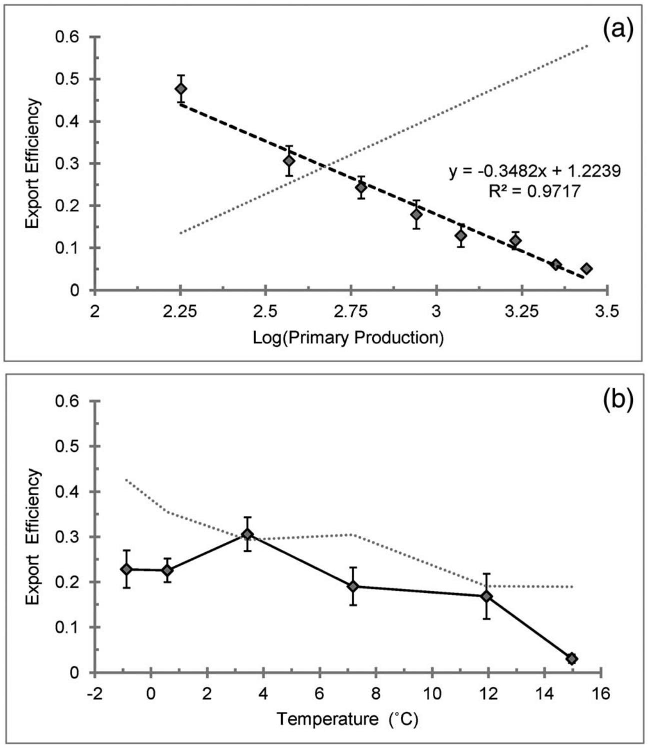

Figure 3. Plots showing the relationship between (a) export efficiency and primary production and (b) export efficiency and temperature for binned flux data. The black lines represent the trend in the binned data. The gray dotted lines represent export efficiencies from Laws-00 model with identical data binning. Error bar shows standard error of the mean.

due to sampling bias such as a decoupling between 24 h primary production incubation methods and ^{234}Th method, which integrates over longer time scales.

[16] To filter out the noise in the export ratios, we binned the data based on the associated rates of total production, 0–250, 250–500, 500–750, 750–1000, 1000–1500, 1500–2000, 2000–2500, and 2500–3000 mg C m^{-2} d^{-1}. The wider bins at higher production rates reflect the density of the data: 50% of the export ratios are associated with production rates less than 750 mg C m^{-2} d^{-1}. The relationship between NPP and export efficiency is significantly robust ($R^2 = 0.97$; $P = 0.000002$) and in support of a strong negative relationship between production and export efficiency in the Southern Ocean (Figure 3a). Thus, for the first time we report a basin-wide trend in export efficiency which is opposite of what these export production models predict (gray line in Figure 3a).

[17] Individual field studies from this region would support this inverse relationship. For example, studies carried out in the Kerguelen Ocean and near Crozet Islands in Southern Ocean showed a trend of increasing export efficiency at the low-productivity site as compared to the high-productivity sites. In the Kerguelen study, the export efficiency was 58% at the non-bloom station compared to 13–48% within the bloom [*Savoye et al.*, 2008]. A similar but less clear-cut trend was evident near Crozet Islands where the export efficiency at 100 m was 16–30% and 21–33% for non-bloom and bloom stations, respectively [*Morris et al.*, 2007]. In the sub-Antarctic and Polar Front Zone south of Tasmania, the more productive region situated in the eastern part of SAZ is associated with lower export efficiencies of about 2–12% compared to the less productive western SAZ and PFZ where the export efficiency varied between 11–53% [*Jacquet et al.*, 2011].

[18] A number of reasons are cited for these high productivity-low export regimes such as differences in trophic structure, grazing intensity, recycling efficiency, high bacterial activity, and increase in DOC export [*Hansell et al.*, 2009], but the exact cause still remains elusive. The most important implication of these observations is that the simplest models of export, which predict an increase in POC flux with increasing NPP, may require additional parameters, different weight of existing parameters, or separate algorithms altogether for different oceanic regimes. To the latter point, the commonly applied Laws-00 food web model does not seem to be appropriate for Southern Ocean, which may be a result of the inclusion of only 11 sites [*Laws et al.*, 2000].

[19] It is important to remember that when comparing a model with global dataset [e.g., *Laws et al.*, 2000; *Laws et al.*, 2011; *Dunne et al.*, 2005], there exists a temperature range of 0 to 28°C, which alone can account for 86% of the variance in the export efficiency [*Laws et al.*, 2000]. However, when the focus is on regional scale like for the Southern Ocean where temperature varies between a narrower range of −2 to 16°C, the relationship between export and production is no longer dominated by the temperature and other factors can become increasingly important. The strong relationship between production and export (Figure 3a), which does not take into account the effect of temperature, points to the fact that temperature has very limited influence on the export efficiency in this region. To filter out the noise in the export ratios, we binned the data based on the associated temperature: −2°C–0°C, 0°C–2°C, 2°C–6°C, 6°C–10°C, 10°C–14°C, and 14°C–18°C. The wider bins at higher temperature reflect the density of the data; 50% of the export ratios in this dataset are associated with temperature less than 2°C. The export efficiency is found to be relatively insensitive to temperature at less than 6°C (Figure 3b). It must be noted that about 75% of our data falls in this range. However, at temperature above 6°C, there appears to a negative relationship ($R^2 = 0.90$, $P = 0.029$) between export efficiency and temperature (Figure 3b). This latter observation is in line with our existing understanding of models that predict a linear decrease in export efficiency with temperature (gray line in Figure 3b). However, the relative insensitivity of export efficiencies at temperature below 6°C has important implication for future climate change scenarios and could mean a lower export potential in the future for regions which are presently at temperatures below the 6°C threshold.

[20] Most export production models assume a steady state system, which may not apply to a dynamic system like the Southern Ocean, especially since most of the samples were collected between October and March when the system is characterized by numerous bloom events. Thus, the deviation from the export ratios predicted by the Law-00 model could be due to the fact that the model is solved for maximum stability under steady state conditions. This results a sharp transition between high and low export ratios at primary production between 570 mg C m^{-2} d^{-1} and 1700 mg C m^{-2} d^{-1} (integrated over 100 m using Redfield

ratio of C/N = 5.7 by weight) at temperature range of 0–10°C [*Laws et al*., 2000]. It must be noted that ~40% of the data shown in Figure 2a fall with the range of the above such primary production rates. However, it can be argued that the Laws-00 model though meant for steady state conditions gives remarkably good estimates for bloom and upwelling conditions of North Atlantic bloom and equatorial Pacific [*Laws et al*., 2000]. This may be because the temperature will influence the rate of decomposition of organic matter regardless of (i) whether the system is in steady state and (ii) the temperature will modulate the export ratio much more strongly in these regions than the colder Southern Ocean.

[21] At present, no single model of global export production does a reasonable job of estimating export production in the Southern Ocean. It appears that neither food web structure nor new production can predict carbon flux with a fair amount of certainty, particularly on the time scales over which the ocean is under nonsteady state conditions [*Rivkin et al*., 1996]. Observational data suggest that the Southern Ocean may have a lower carbon export potential than has been predicted by existing models, especially in the higher productivity regimes. Clearly, additional research is required to improve our understanding of the upper ocean carbon export in this region. In the absence of any mechanistic models that can adequately explain the observational dataset from Southern Ocean, we recommended that the simple relationship between export efficiency and production (shown in Figure 3a) be used for predicating export flux from satellite-derived primary production.

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